Experimental test of the high frequency quantum shot noise theory in a Quantum Point Contact

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We report on direct measurements of the electronic shot noise of a Quantum Point Contact (QPC) at frequencies ν in the range 4-8 GHz. The very small energy scale used ensures energy independent transmissions of the few transmitted electronic modes and their accurate knowledge. Both the thermal energy and the QPC drain-source voltage V_{ds} are comparable to the photon energy $h\nu$ leading to observation of the shot noise suppression when $V_{ds} < h\nu/e$. Our measurements provide the first complete test of the finite frequency shot noise scattering theory without adjustable parameters.

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Pauli's exclusion principle has striking consequences on the properties of quantum electrical conductors. In an ideal quantum wire, it is responsible for the quantization of the conductance by requiring that at most one electron (or two for spin degeneracy) occupies the regularly time-spaced wave-packets emitted by the contacts and propagating in the wire [1]. Concurrently, at zero temperature, the electron flow is noiseless [2, 3] as can be observed in ballistic conductors [4, 5, 6]. In more general quantum conductors, static impurities diffract the noiseless electrons emitted by the contacts. This results in a partition of the electrons between transmitted or reflected states, generating quantum shot noise [1, 2, 3, 7, 8]. However, Pauli's principle possesses more twists to silence electrons. At finite frequency ν, detection of current fluctuations in an external circuit at zero temperature requires emission of photons corresponding to a finite energy cost $h\nu$ [9]. For drain-source contacts biased at voltage V_{ds}, a sharp suppression is expected to occur when the photon energy $h\nu$ is larger than eV_{ds} as an electron emitted by the source can not find an empty state in the drain to emit such a photon [9, 10, 11]. Another striking consequence of Pauli's principle is the prediction of non-classical photon emission for a conductor transmitting only one or few electronic modes. It has been shown that in the frequency range $eV_{ds}/2h < \nu < eV_{ds}/h$, the population of a photon mode obeys a sub-Poissonian statistics inherited from the electrons [12]. Investigating quantum shot noise in this high frequency regime using a Quantum Point Contact (QPC) to transmit few modes is thus highly desirable.

The first step is to check the validity of the above prediction based on a non-interacting picture of electrons. For 3D or 2D wide conductors with many quantum channels which are good Fermi liquids, one expects this non-interacting picture to work well. Indeed, the eV_{ds}/h singularity has been observed in a 3D diffusive wire in the shot noise derivative with respect to bias voltage [13]. However, for low dimensional systems like 1D wires or conductors transmitting one or few channels, electron interactions give non-trivial effects. Long 1D wires defined in 2D electron gas or Single Wall Carbon Nanotubes become Luttinger liquids. Long QPCs exhibit a 0.7 conductance anomaly [14], and a low frequency shot noise [15] compatible with Kondo physics [16]. Consequently, new characteristic frequencies may appear in shot noise reflecting electron correlations. Another possible failure of the non-interacting finite frequency shot noise model could be the back-action of the external circuit. For high impedance circuits, current fluctuations implies potential fluctuations at the contacts [17]. Also, the finite time required to eliminate the sudden drain-source charge build-up after an electron have passed through the conductor leads to a dynamical Coulomb blockade for the next electron to tunnel. A peak in the shot noise spectrum at the electron correlation frequency I/e is predicted for a tunnel junction connected to a capacitive circuit [18]. Other timescales may also be expected which affect both conductance [19] and noise [20] due to long range Coulomb interaction or electron transit time. This effects have been recently observed for the conductance [21] .

The present work aims at giving a clear-cut test of the non-interacting scattering theory of finite frequency shot noise using a Quantum Point Contact transmitting only one or two modes in a weak interaction regime. It provides the missing reference mark to which further experiments in strong interaction regime can be compared in the future. We find the expected shot noise suppression for voltages $\leq h\nu/e$ in the whole 4-8 GHz frequency range. The data taken for various transmissions perfectly

agree with the finite temperature, non-interacting m
with no adjustable parameter. In addition to pr
a stringent test of the theory, the technique deve
is the first step toward the generation of non-clas
photons with QPCs in the microwave range [12].
detection technique uses cryogenic linear amplific
followed by room temperature detection. The ele
temperature much lower than $h\nu/k_B$, the small en
scale used ($eV_{ds} \ll 0.02E_F$) ensuring energy indepen
transmissions, the high detection sensitivity, and th
solute calibration allow for direct comparison with
ory without adjustable parameters. Our technique d
from the recent QPC high frequency shot noise mea
ments using on-chip Quantum Dot detection in the 10-
150 GHz frequency range [22]. Although most QPC shot
noise features were qualitatively observed validating this
promising method, the lack of independent determina-
tion of the QPC-Quantum Dot coupling, and the large
voltage used from 0.05 to $0.5E_F$ making QPC transmis-
sions energy dependent, prevent quantitative comparison
with shot noise predictions. However, Quantum Dot de-
tectors can probe the vacuum fluctuations via the stim-
ulated noise while the excess noise detected here only
probes the emission noise [9, 10].

The experimental set-up is represented in fig. 1. A
two-terminal conductor made of a QPC realized in a
2DEG in GaAs/GaAlAs heterojunction is cooled at 65
mK by a dilution refrigerator and inserted between two
transmission lines. The sample characteristics are a 35
nm deep 2DEG with 36.7 m²V⁻¹s⁻¹ mobility and 4.4
10¹⁵ m⁻² electron density. Interaction effects have been
minimized by using a very short QPC showing no sign
of 0.7 conductance anomaly. In order to increase the
sensitivity, we use the microwave analog of an optical re-
flective coating. The contacts are separately connected
to 50 Ω coaxial transmission lines via two quarter wave
length impedance adapters, raising the effective input
impedance of the detection lines to 200 Ω over a one
octave bandwidth centered on 6 GHz. The 200 Ω elec-
tromagnetic impedance is low enough to prevent dynam-
ical Coulomb blockade but large enough for good cur-
rent noise sensitivity. The transmitted signals are then
amplified by two cryogenic Low Noise Amplifiers (LNA)
with $T_{\text{noise}} \simeq 5$K. Two rf-circulators, thermalized at
mixing chamber temperature protect the sample from
the current noise of the LNA and ensure a circuit en-
vironment at base temperature. After further amplifi-
cation and eventually narrow bandpass filtering at room
temperature, current fluctuations are detected using two
calibrated quadratic detectors whose output voltage is
proportional to noise power. Up to a calculable gain
factor, the detected noise power contains the weak sam-
ple noise on top of a large additional noise generated by
the cryogenic amplifiers. In order to remove this back-
ground, we measure the excess noise $\Delta S_I(\nu, T, V_{ds}) = S_I(\nu, T, V_{ds}) - S_I(\nu, T, 0)$. Practically, this is done by
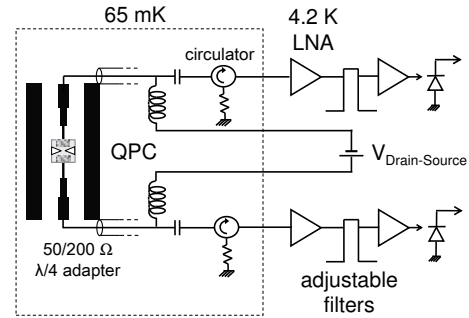

FIG. 1: Schematic diagram of the measurement set-up. See text for details.

applying a 93 Hz 0-V_{ds} square-wave bias voltage on the
sample through the DC input of a bias-T, and detecting
the first harmonic of the square-wave noise response of
the detectors using lock-in techniques. In terms of noise
temperature referred to the 50 Ω input impedance, an
excess noise $\Delta S_I(\nu, T, V_{ds})$ gives rise to an excess noise
temperature

$$\Delta T_n^{50\Omega}(\nu, T, V_{ds}) = \frac{Z_{\text{eff}} Z_{\text{sample}}^2 \Delta S_I(\nu, T, V_{ds})}{(2Z_{\text{eff}} + Z_{\text{sample}})^2}. \quad (1)$$

Eq. 1 demonstrates the advantage of impedance match-
ing : in the high source impedance limit $Z_{\text{sample}} \gg Z_{\text{eff}}$,
the increase in noise temperature due to shot noise is
proportional to Z_{eff}. Our set up ($Z_{\text{eff}} = 200\Omega$) is thus
four times more efficient than a direct connection of the
sample to standard 50 Ω transmission lines. Finally, the
QPC differential conductance G is simultaneously mea-
sured through the DC input of the bias-Tee using low
frequency lock-in technique.

The very first step in the experiment is to characterize
the QPC. The inset of fig. 4 shows the differential con-
ductance versus gate voltage when the first two modes
are transmitted. As the experiment is performed at zero
magnetic field, the conductance exhibits plateaus quan-
tized in units of $G_0 = 2e^2/h$. The short QPC length
(80 nm) leads to a conductance very linear with the
low bias voltage used ($\delta G/G \leq 6\%$ for $V_{ds} \leq 80\mu$V for
$G \simeq 0.5\,G_0$). It is also responsible for a slight smooth-
ing of the plateaus. Each mode transmission is extracted
from the measured conductance (open circles) by fitting
with the saddle point model (solid line) [23].

We then set the gate voltage to obtain a single mode
at half transmission corresponding to maximum electron
partition ($G \simeq 0.5\,G_0$). Fig. 2 shows typical excess noise
measured at frequencies 4.22 GHz and 7.63 GHz and
bandwidth 90 MHz and 180 MHz. We note a striking
suppression of shot noise variation at low bias voltage,
and that the onset of noise increases with the measure-
ment frequency. This is in agreement with the photon
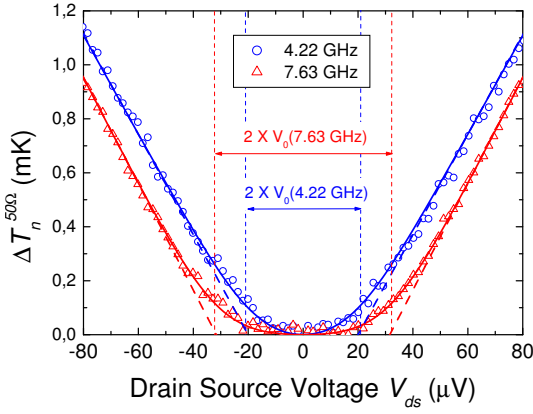suppression of shot noise in a non-interacting system.

FIG. 2: Color Online. Excess noise temperature as a function of bias voltage, measured at 4.22 GHz (open circles) and 7.63 GHz (open triangles). The dashed lines represent the linear fits to the data, from which the threshold V_0 is deduced. The solid lines represent the expected excess noise $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$, using $T_e(V_{ds})$ obtained from eq. 5. The frequency dependent coupling is the only fitting parameter.

FIG. 3: Onset V_0 as a function of the observation frequency. The experimental uncertainty corresponds to the size of the symbols. The dashed lines correspond to the low ($eV_0 = 2k_BT$) and high ($eV_0 = h\nu$) frequency limits, and the solid line is a fit to theory, with the electronic temperature as only fitting parameter.

The expected excess noise reads

$$\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i(1 - D_i) \left(\frac{h\nu - eV_{ds}}{e^{(h\nu - eV_{ds})/k_B T} - 1} \right.$$
$$\left. + \frac{h\nu + eV_{ds}}{e^{(h\nu + eV)/k_B T} - 1} - \frac{2h\nu}{e^{h\nu/k_B T} - 1} \right). \quad (2)$$

It shows a zero temperature singularity at $eV_{ds} = h\nu$: $\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i(1 - D_i)(eV_{ds} - h\nu)$ if $eV_{ds} > h\nu$ and 0 otherwise. At finite temperature, the singularity is thermally rounded. At high bias ($eV_{ds} \gg h\nu, k_B T$), equation 2 gives an excess noise

$$\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i(1 - D_i) (eV_{ds} - eV_0) \quad (3)$$
$$\text{with} \qquad eV_0 = h\nu \coth(h\nu/2k_B T). \quad (4)$$

In the low frequency limit, the threshold V_0 characterizes the transition between thermal noise and shot noise ($eV_0 = 2k_BT$), whereas in the low temperature limit, it marks the onset of photon suppressed shot noise ($eV_0 = h\nu$). As shown on fig. 2, V_0 is determined by the intersection of the high bias linear regression of the measured excess noise and the zero excess noise axis. Fig. 3 shows V_0 for eight frequencies spanning in the 4-8 GHz range for $G \simeq 0.5\,G_0$. Eq. 4 gives a very good fit to the experimental data. The only fitting parameter is the electronic temperature $T_e = 72$ mK, very close to the fridge temperature $T_{\text{fridge}} = 65$ mK. We will show that electron heating can account for this small discrepancy.

To get a full comparison with theory, we now investigate the influence of the transmissions of the first two electronic modes of the QPC. To do so, we repeat the same experiment at fixed frequency (here we used a 5.4-5.9 GHz filter) for different sample conductances. The
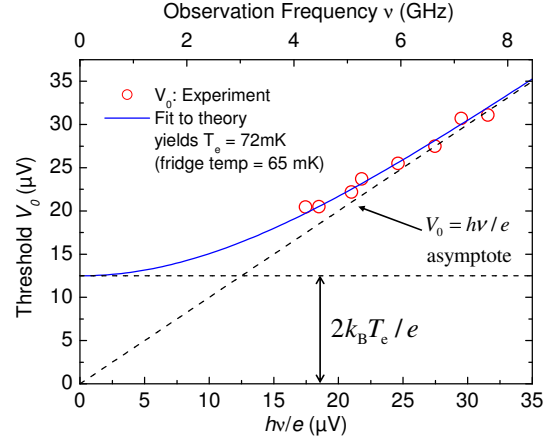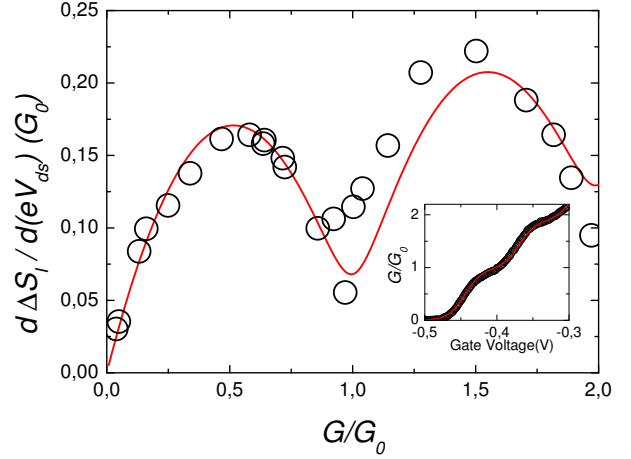

FIG. 4: Open circles: $d\Delta S_I/d(eV_{ds})$ deduced from $\Delta T_n^{50\Omega}$. Full line : theoretical prediction. The only fitting parameter is the microwave attenuation. The experimental uncertainty corresponds to the size of the symbols. Inset : Open circles : conductance of the QPC as a function of gate voltage. Solid Line : fit with the saddle point model [23].

noise suppression at $V_{ds} \leq h\nu/e$ is the only singularity we observe, independently of the QPC conductance G. Fig. 4 shows the derivative with respect to eV_{ds} of the excess noise $d\Delta S_I/d(eV_{ds})$ deduced from the excess noise temperature measured between 50 μV and 80 μV. This energy range is chosen so that eV_{ds} is greater than $h\nu$ by at least $5k_BT_{\text{fridge}}$ over the entire frequency range. The data agree qualitatively with the expected $D(1-D)$ dependence of pure shot noise, showing maxima at conductances $G = 0.5\,G_0$, and $G = 1.5\,G_0$, and minima at conductances $G = G_0$ and $G = 2\,G_0$. The short QPC is responsible for the non zero minima as, when the second mode starts to transmit electrons, the first one has

not reached unit transmission (inset of fig. 4). However, eq. 2 is not compatible with a second maximum higher than the first one, which is due to electron heating. The dimensions of the 2-DEG being much larger than the electron-electron energy relaxation length, but much smaller than electron-phonon energy relaxation length, there is a gradient of electronic temperature from the QPC to the ohmic metallic contacts assumed at the fridge temperature. Combining the dissipated power IV_{ds} with the Wiedemann-Franz law, one gets [5, 24]

$$T_e^2 = T_{\text{fridge}}^2 + \frac{24}{\pi^2} \frac{G}{G_m} \left(1 + \frac{2G}{G_m}\right) \left(\frac{eV_{ds}}{2k_B}\right)^2 \qquad (5)$$

where G_m stands for the *total* conductance of the 2D leads, estimated from measurements to be 12 mS $\pm 20\%$. The increased noise temperature is then due to both shot noise and to the increased thermal noise. For a fridge temperature of 65 mK and $G = G_0/2$, the electronic temperature will increase from 69 mK to 77 mK as V_{ds} increases from 50 μV to 80 μV. This accounts for the small discrepancy between the fridge temperature and the electron temperature deduced from the variation of V_0 with frequency. As G increases, the effect is more important, as can be seen both in fig. 4 and eq. 5. The solid line in figure 4 gives the average derivative with respect to eV_{ds} of the total expected excess noise $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$, using the attenuation of the signal as a free parameter. The agreement is quite satisfactory, given the accuracy of the saddle point model description of the QPC transmission. We find a 4.7 dB attenuation, which is in good agreement with the expected 4 ± 1 dB deduced from calibration of the various elements of the detection chain. Moreover, the voltage dependent electron temperature obtained from eq. 5 can also be used to evaluate $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$ as a function of V_{ds} at fixed sample conductance $G = 0.5\,G_0$. The result, as shown by the solid lines of fig. 2, is in excellent agreement with experimental observations.

In conclusion, we performed the first direct measurement of the finite frequency shot noise of the simplest mesoscopic system, a QPC. Accurate comparison of the data with non-interacting shot noise predictions have been done showing perfect quantitative agreement. Even when a single mode is transmitted, no sign of deviation related to interaction was found, as expected for the experimental parameters chosen for this work. We have also shown that accurate and reliable high frequency shot noise measurements are now possible for conductors with impedance comparable to the conductance quantum. This opens the way to high frequency shot noise characterization of Carbon Nanotubes, Quantum Dots or Quantum Hall samples in a regime where microscopic frequencies are important and will encourage further theoretical work in this direction. Our set-up will also allow to probe the statistics of photons emitted by a phase coherent single mode conductor.

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